

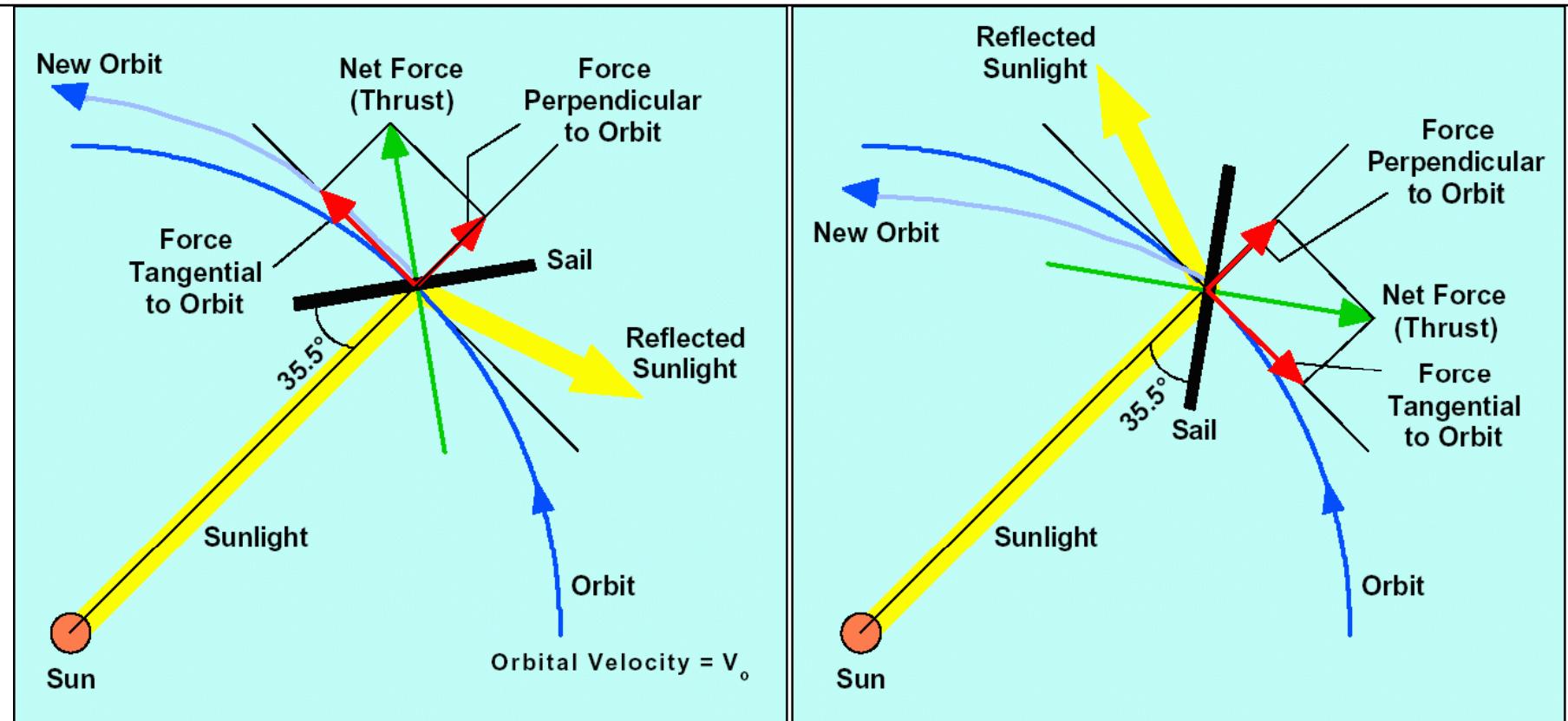


Solar Sailing

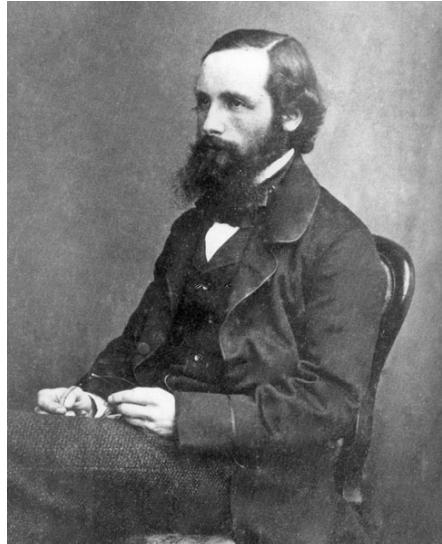
***Les Johnson
September 2008***

Solar Sails: From Science Fiction to Reality

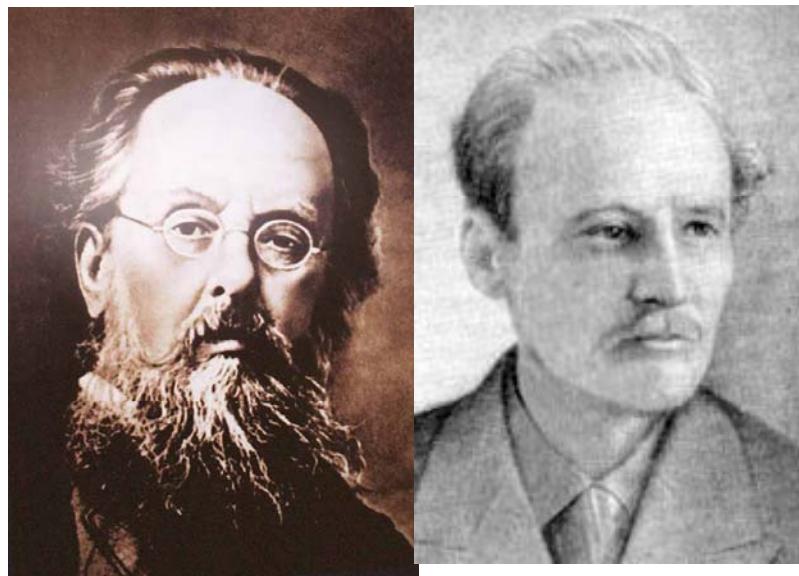
- Solar sails use photon “pressure” of force on thin, lightweight reflective sheet to produce thrust; ideal reflection of sunlight from surface produces **9 Newtons/km²** at 1 AU [**<0.2 oz per football field**]
- Net force on solar sail perpendicular to surface
- As long as the sun shines, a solar sail will be able to produce thrust



Solar Sailing Is Not A New Idea



- James Clerk Maxwell (England), who developed the modern theory of electromagnetism in the 1860's, proved that light could exert pressure.
- Konstantin Tsiolkovsky (Russia) first discussed solar sailing; Fridrickh Tsander (Russia) wrote in 1924, "For flight in interplanetary space I am working on the idea of flying, using tremendous mirrors of very thin sheets, capable of achieving favorable results."



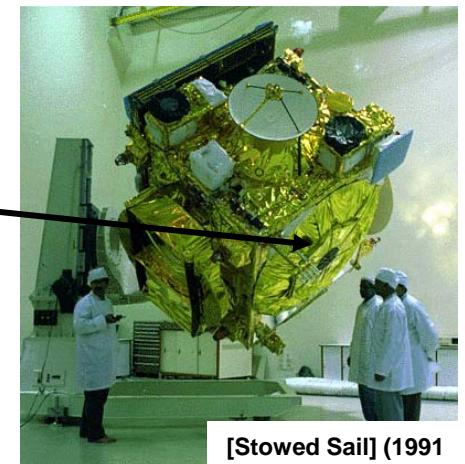
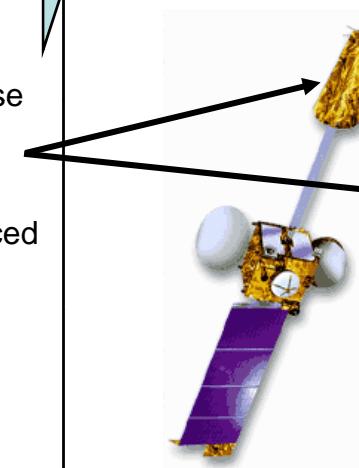
Solar Sail Technology History

Used Since 1962

- Solar Sailing was initially developed at JPL as a measure to save the Mariner 10 mission which had lost a large portion of its propellant margin when the star tracker locked on to floating debris instead of Canopus. The mission went on to flyby Venus and three encounters with Mercury. Its successful implementation on that mission led to it being declared a mature technology, ready for application to future NASA missions in 1978.
- Several Comsats (e.g. INSAT 2E) operating today in GEO use solar pressure to unload momentum wheels or offset solar torques on asymmetric solar arrays.
- Chosen for Halley Comet Rendezvous in 1985, it was replaced by a chemical rocket in phase B due to launch date/window pressure
- Japanese
 - developing 50 meter sail to combine with an ion thruster for outer planet missions
 - Have flown sounding rocket, balloon, and LEO Polar orbit development experiments
- Joint NASA/NOAA/USAF proposal to NMP ST5 fell in the 11th hour when USAF/NASA/NOAA partnership collapsed
- Planetary society launched a flight experiment and a full system on converted Russian Volna sub-launched missiles. Unfortunately both boosters had stage separation failures.



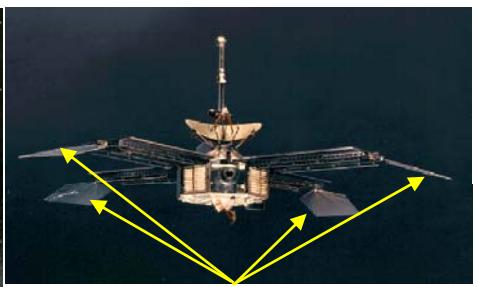
Mariner 10: "the solar sailing technique for conservation of attitude control gas was improvised successfully and thereby qualified as a technique for use in future missions." – Bruce Murray, Flight to Mercury, Columbia University Press 1977, page 142.



[Stowed Sail] (1991)

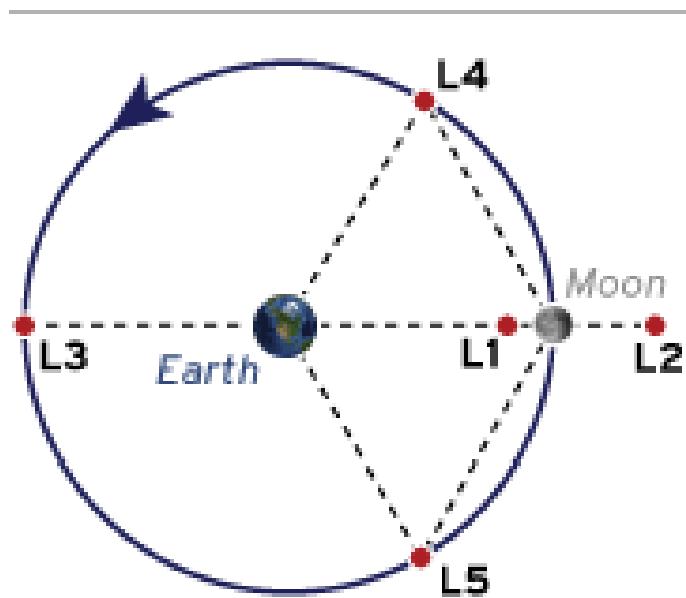


Mariner 2 Dacron
Solar Sail (1962)



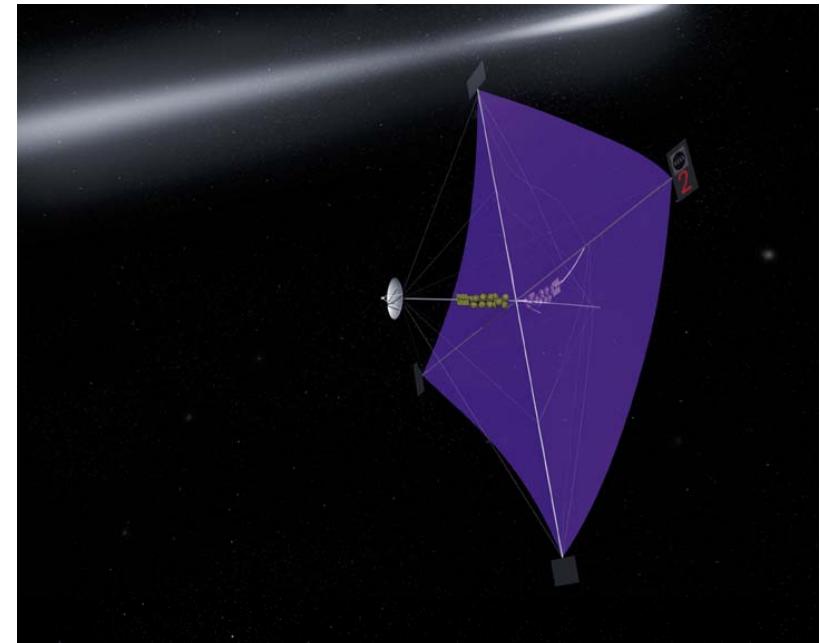
solar sails on Mariner IV (1964)

Studying the Sun: L-1 Diamond



Source: NASA

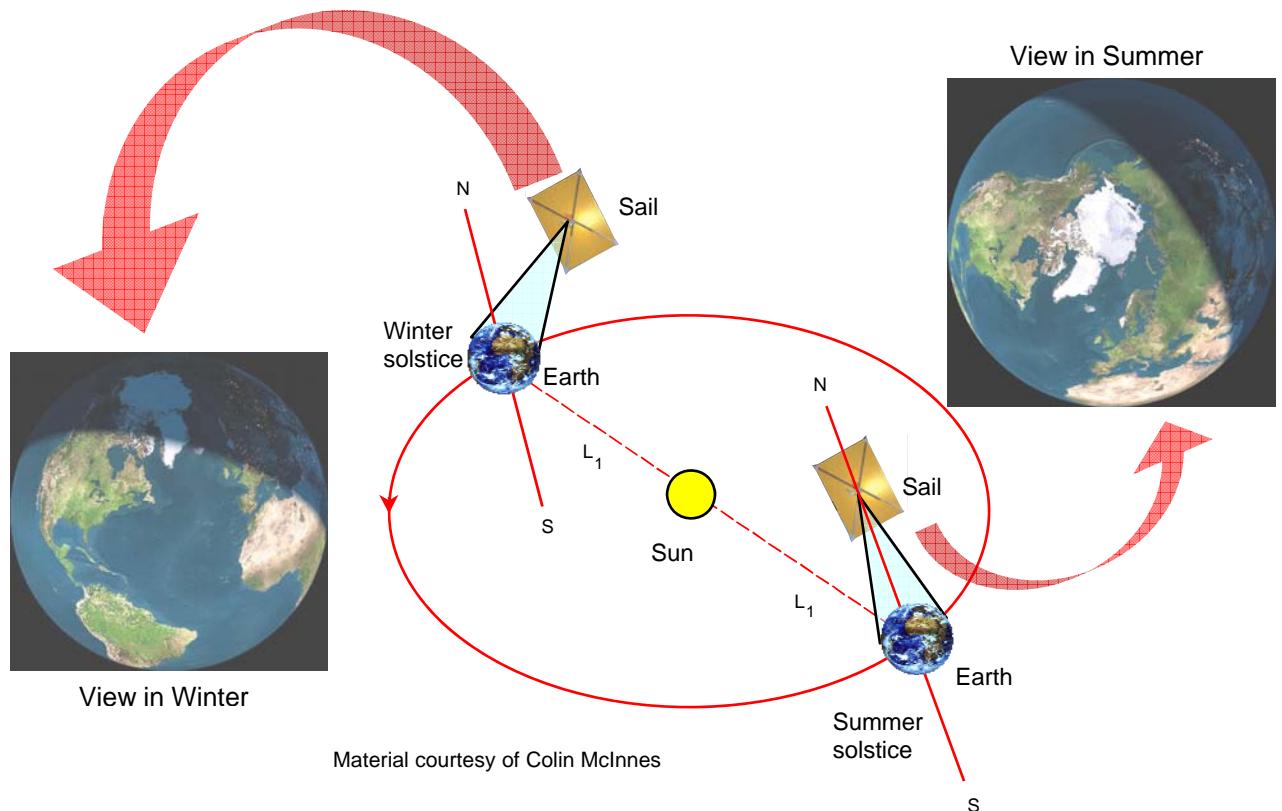
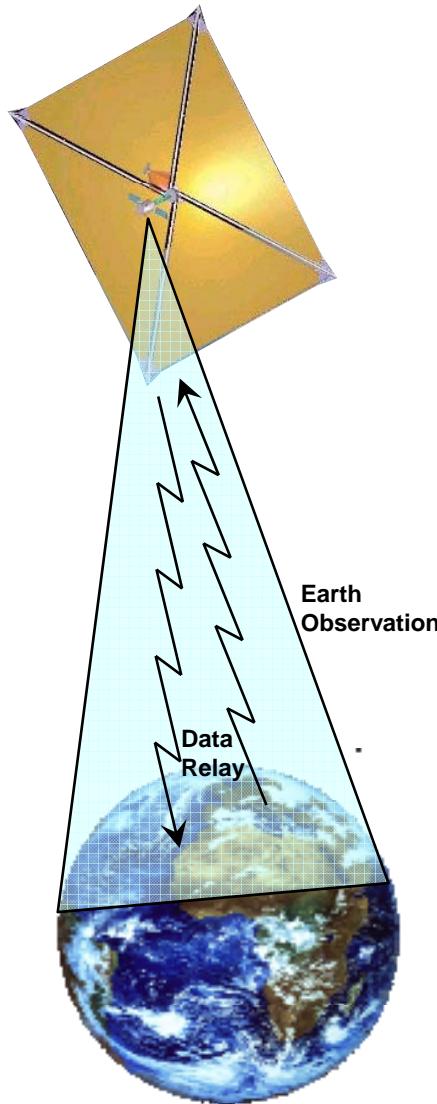
MSNBC



- 4 solar sails could provide continuous observations of the sun

Pole Sitter Mission

- Continual coverage of the polar regions with no propellant usage!
- Altitudes ranging from 0.75 million km to 3.5 million km, depending on sail performance and inclination chosen



Very Large Solar Sails With A Very Close Solar Approach May Enable Interstellar Travel



- 100-km class sail unfurled at less than 0.2 AU may enable a trip to the nearest star in under 1000 years.
- 1000 years ago...
 - China was the world's most populous empire. By the late 11th century, the Song Dynasty had a total population of some 101 million people, an average annual iron output of 125,000 tons/year
 - The Islamic world was experiencing a Golden Age and continued to flourish under the Arab Empire
 - Leif Ericson landed in North America
 - Oslo Norway was founded and lots of wars were fought in Europe
- We have recorded history going back 1000 years and will likely know to turn on the radio to listen for the probe “calling home.”

Laser Sails for Interstellar Travel

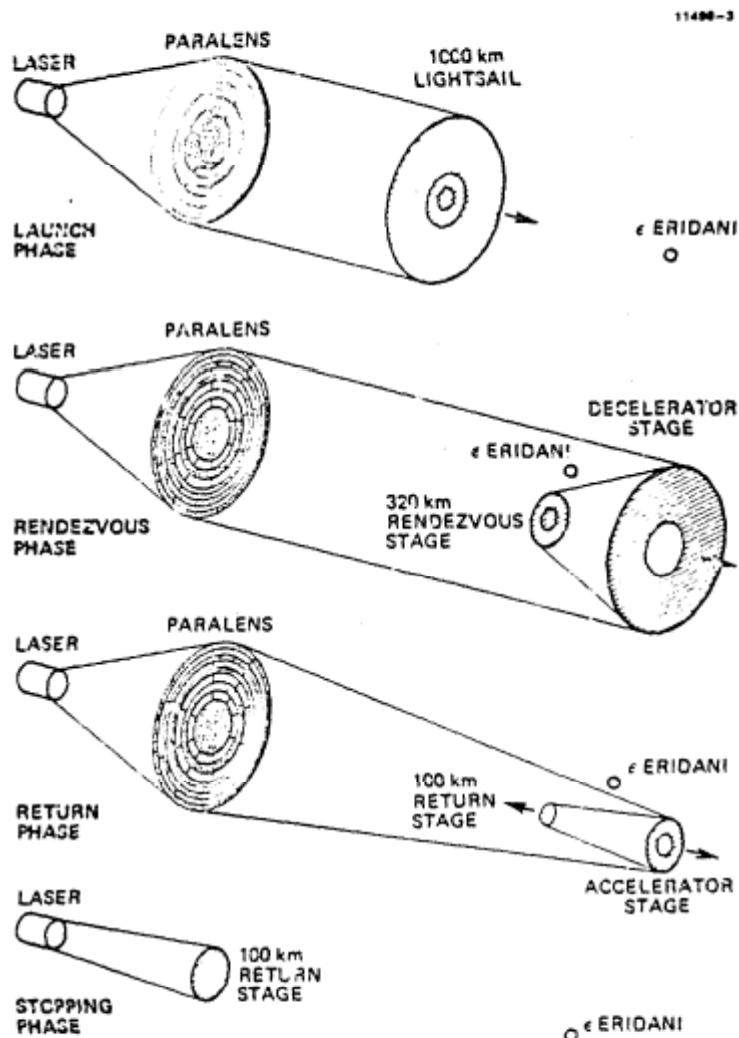
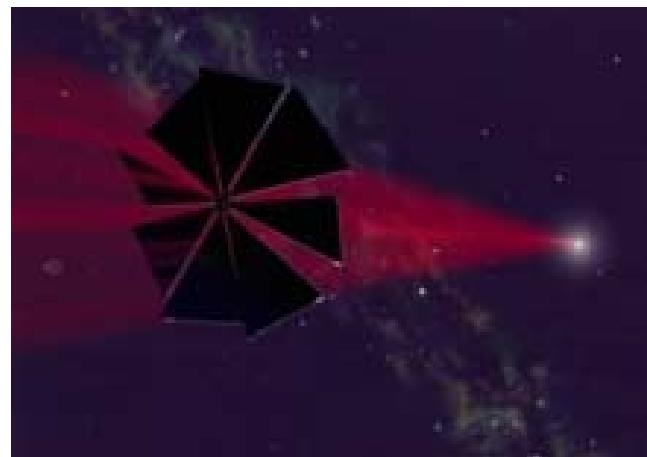
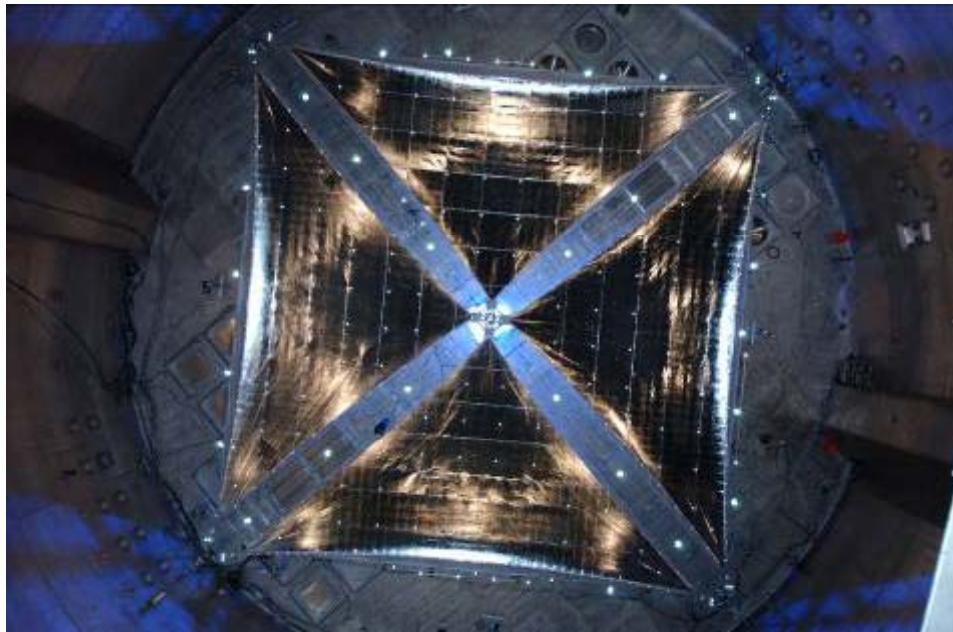


Figure A-2. Roundtrip Interstellar Travel Using Laser-Pushed Lightsails.

- Sails driven by space-based high power lasers may shorten the trip time to under 1000 years

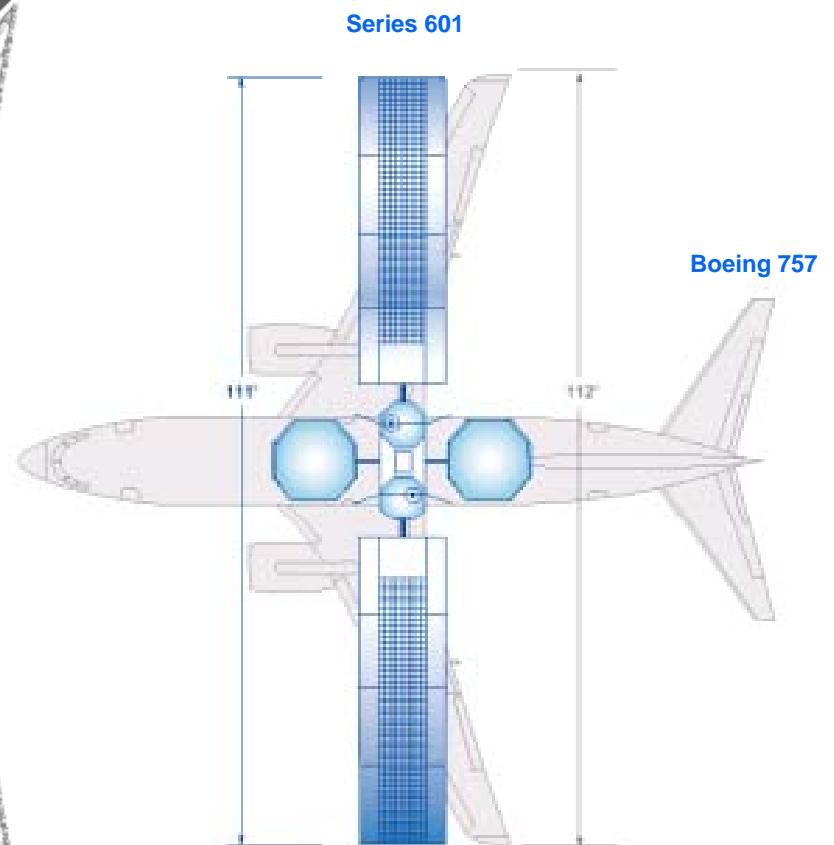
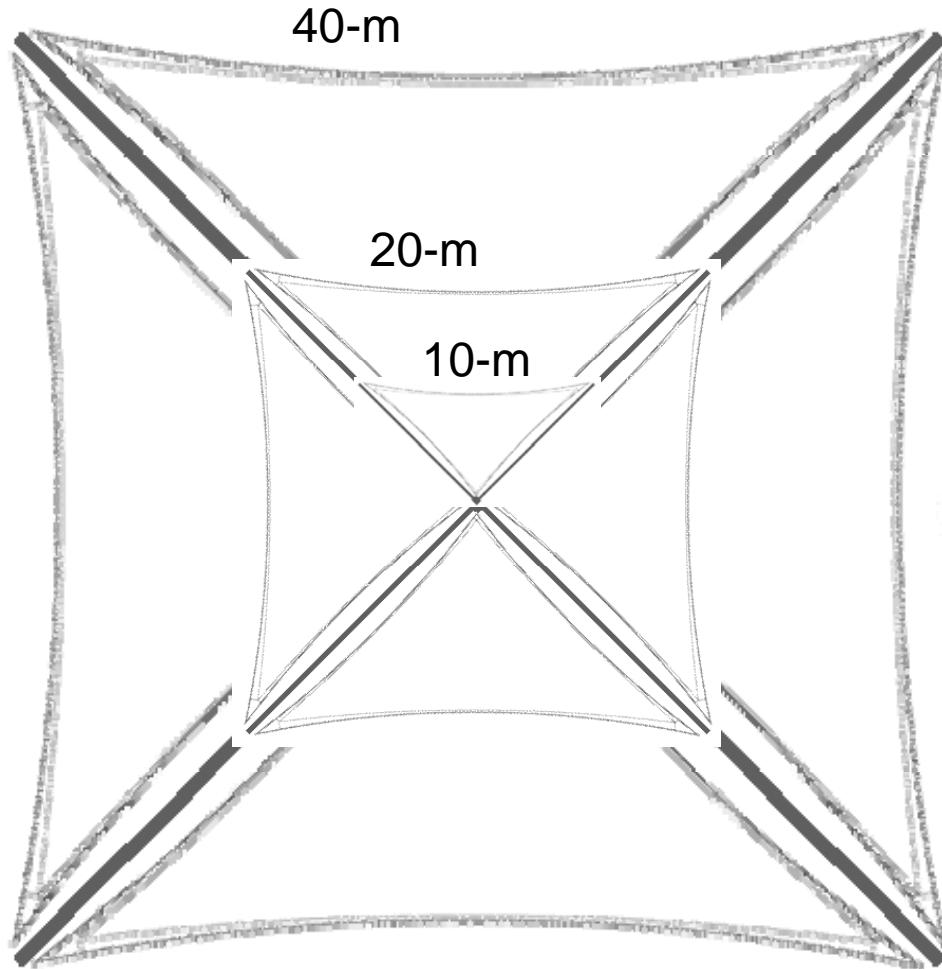


Solar Sail Propulsion Technology Status



- **Technology Area Status:**
 - Two competing teams designed, fabricated, and tested solar sails and performed system level ground demonstrations:
 - 10 m system ground demonstrators were developed and tested in 2004.
 - 20 m system ground demonstrators designed, fabricated, and tested under thermal vacuum conditions in 2005.
 - Developed and tested high-fidelity computational models, tools, and diagnostics.
 - Multiple efforts completed: materials evaluation, optical properties, long-term environmental effects, charging issues, and assessment of smart adaptive structures.

10, 20, and 40-m Solar Sail Systems

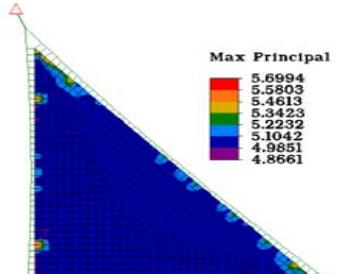


SRS Solar Sail Membrane Features

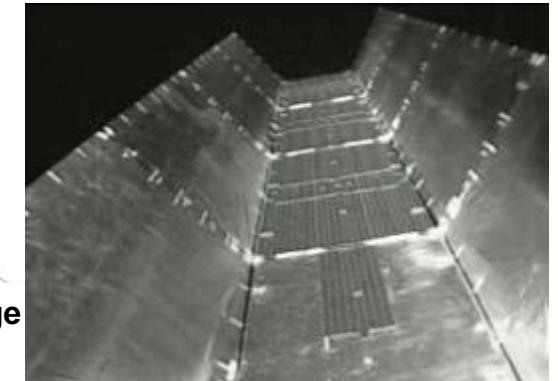
Membrane Design:

4-quadrant planar sail

- Compliant Border interface between edge cable and membrane
 - Shear insensitive, Cord/Material CTE mismatch insensitive
 - Thermal Gradient insensitive



FEM of Parabolic Edge



Sail Material: **CP1 Polyimide**

- High Operating Temperature (>200° C)
- UV Stable
- Essentially Inert
- Soluble (Wet Process), modifiable with variety additives - improve conductivity and thermal properties
- **2.5 micron polyimide**
- **Flight Proven --- flying on Numerous GEOCOM satellites**

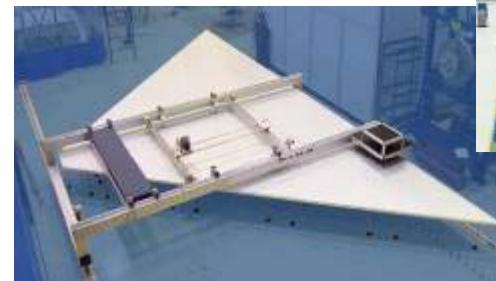


IMG_1123.J
Sail with Compliant Border

160 m² of film per satellite.
Film Is 1 mil material supported by 5 mil edge designs



Sail Production



SRS CNC Seaming System

Sail Construction Methods:

A gossamer film construction similar to gusseted, reflective blankets flying on numerous GEOCOM satellites

- Scalable Construction Methods --- current system >20m
- Adhesive less Bonding Methods --- eliminates sticking and contamination risks.

L'Garde Solar Sail Development

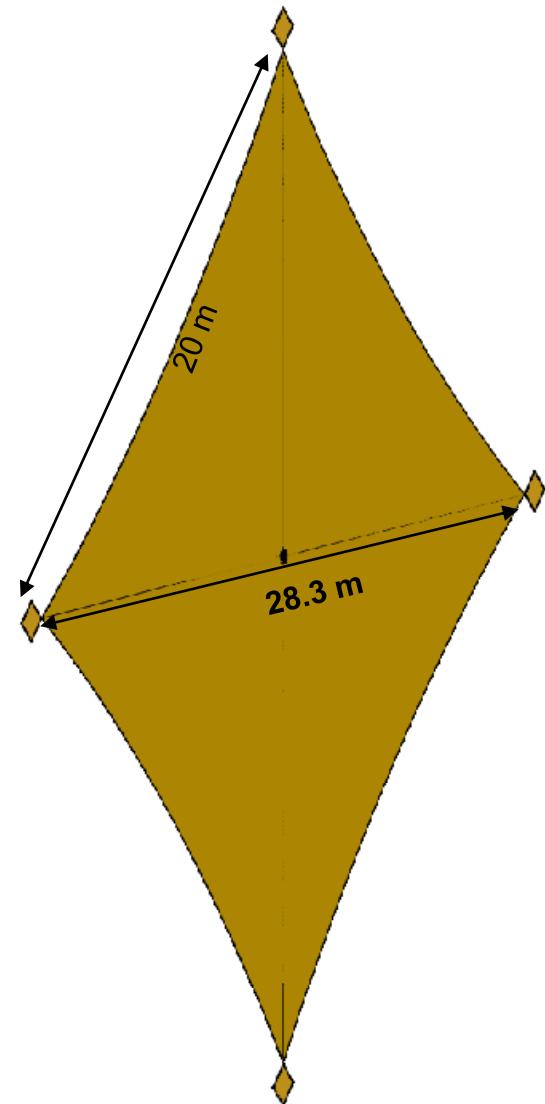
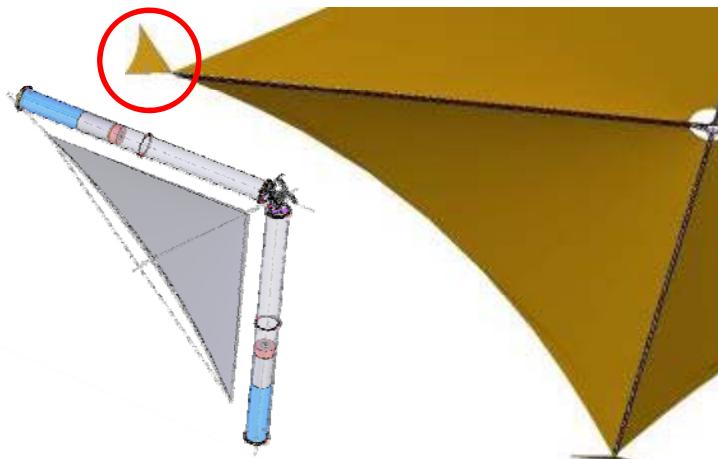
◆ PI: David (Leo) Lichodziejewski, L'Garde, Inc.

◆ Technical Team:

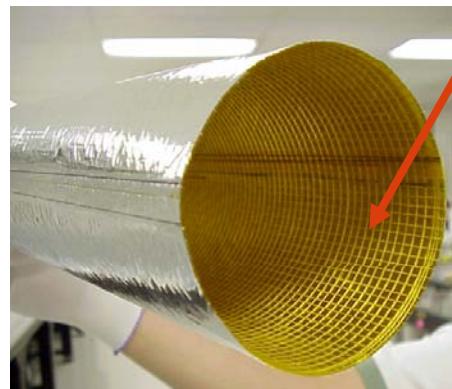
- L'Garde, Inc. (Tustin, CA) systems engineering and inflatable truss
- Ball Aerospace & Tech Corp. (Boulder, CO) mission eng. & bus design
- LaRC (Hampton, VA) sail modeling & testing
- JPL (Pasadena, CA) mission planning & space hazards

◆ Overall Strategy

- Concept Leveraged ST-5 Phase A and Team Encounter experience
 - Sail membrane, AL coated 2 μm Mylar attached with stripped net
 - Lightweight Boom With Sub-Tg Rigidization
 - 4 Vane Thrust Vector Control



Beam Design



Load bearing longitudinal uni-directional fibers

- Fibers impregnated with resin (rigid below -20° C)
- 0.48 AU design requires greater fiber density to withstand loads from the increased solar flux

Spiral wrap

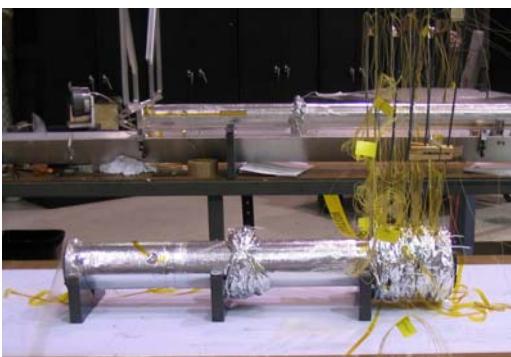
- Stabilizes longitudinal fibers
- Allows over-pressurization for deployment anomalies

Bonded Kapton bladder and Mylar

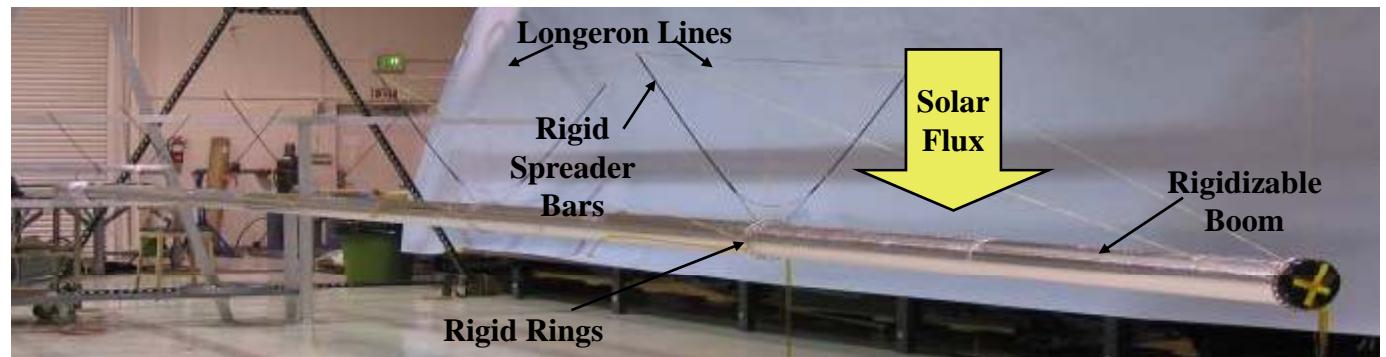
- Encapsulation "skin" carries shear
- Aircraft fuselage like structure

Beam Structure

- Sail structure is stressed for solar loading in one direction for mass efficiency
- Truss system comprised of mostly tension elements, minimal rigid components
- Highly mass efficient, ~36g/m linear density

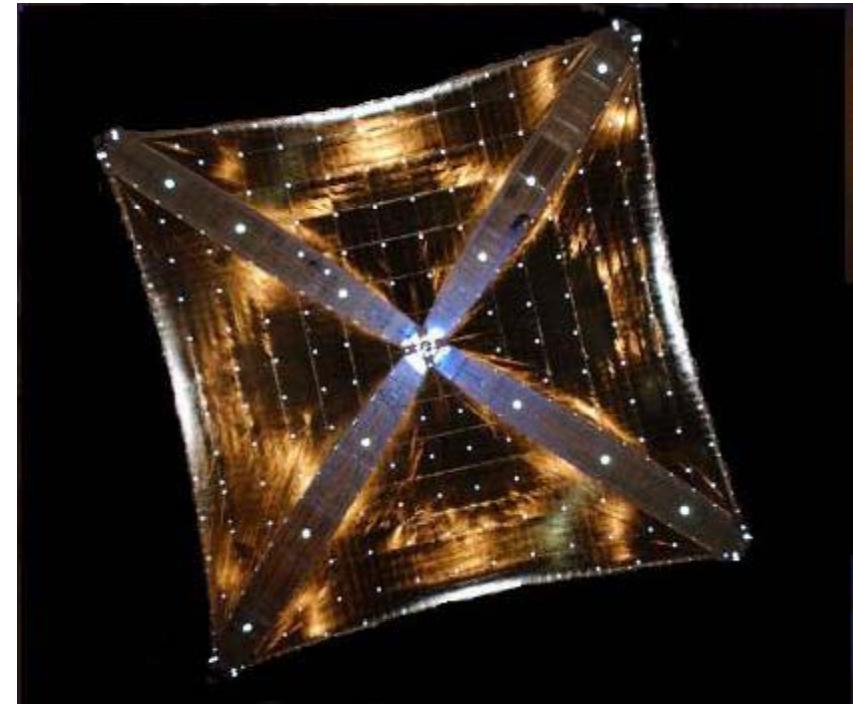
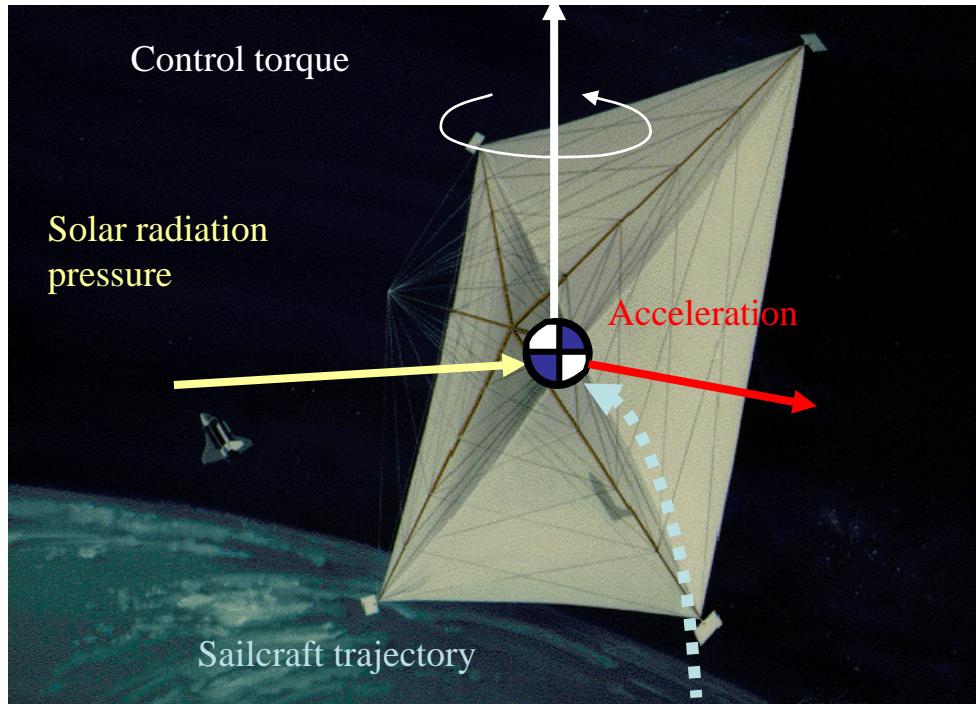


Stowed 7 m boom (~.5 m)



Deployed 7 m boom

Solar Sail Subsystem Development



Solar Sail Spaceflight Simulation Software (S5)

Developed an integrated simulation and analysis software tool for optimal design of solar sail trajectories and for evaluation of guidance navigation and control strategies.

Optical Diagnostic System (ODS)

Developed a lightweight integrated instrumentation package to allow measurement of sail shape, tension and temperature; boom & sail vibration modes and stress; and deployment monitoring.

Solar Sail Subsystem Development– cont.

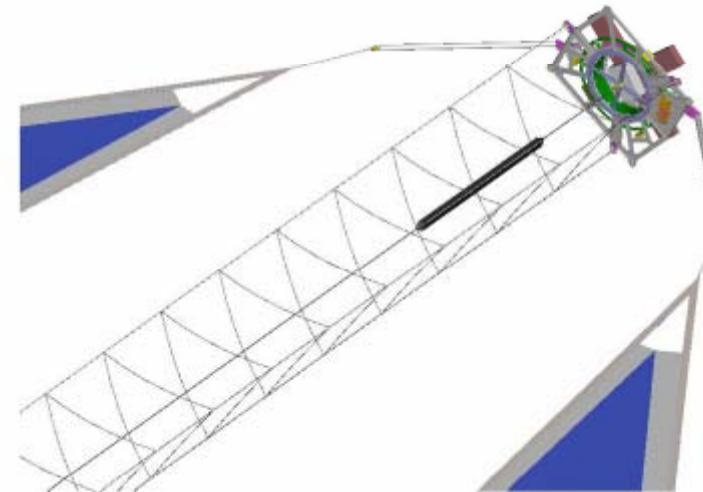


Samples prior to UV exposure

Material Testing

Characterized engineering performance of candidate SS materials at .5 and 1 AU, gauging material property tolerances after exposure to simulated mission-specific charged-particle and micrometeoroid environments.

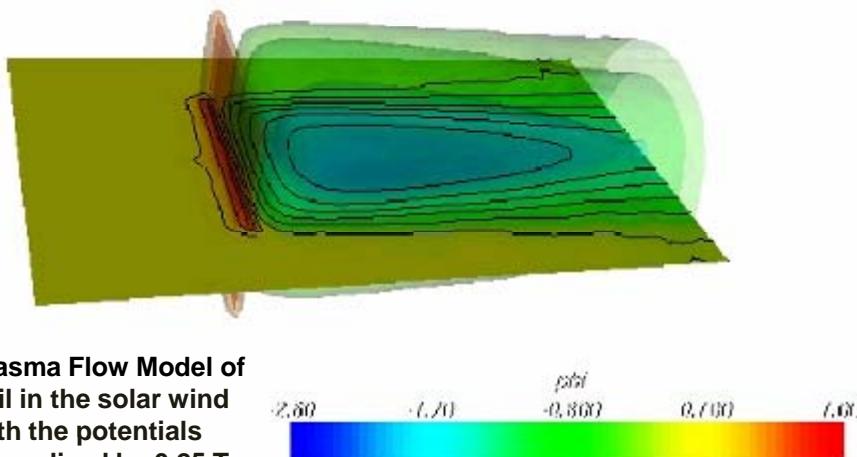
Able's Solar Sail Mast with a Trim Control Mass (TCM), Roll Spreader Bars (RSBs), and microPPTs



Development of a Lightweight Robust SACS and a Software Toolkit for Solar Sails

Developed of a highly integrated, low cost, low mass, low volume, and low power attitude determination and control system and develop a high-fidelity multi-body modeling and simulation software toolkit.

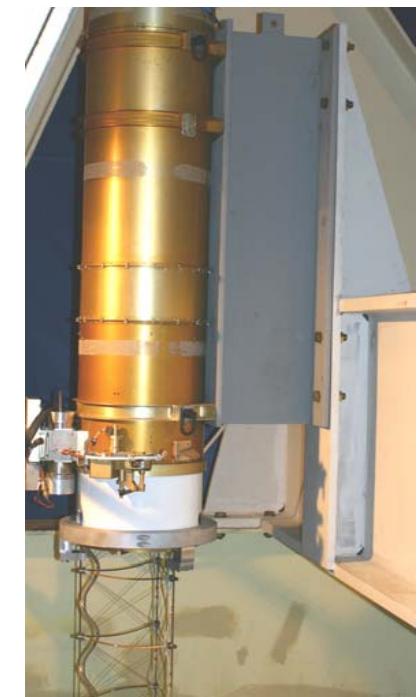
Solar Sail Subsystem Development– cont.



Sail Charging Analysis

Developed environmental and sail configuration models and design guideline criteria for solar sails. Conduct laboratory assessment of potential for destructive charging fields and arcing events within the sail and surrounding environment.

Smart Adaptive Structures
Identified nonlinear mechanism for existing 40 meter coilable boom.
Assess potential for control structures interactions.



Mounted SAFE Mast Canister System

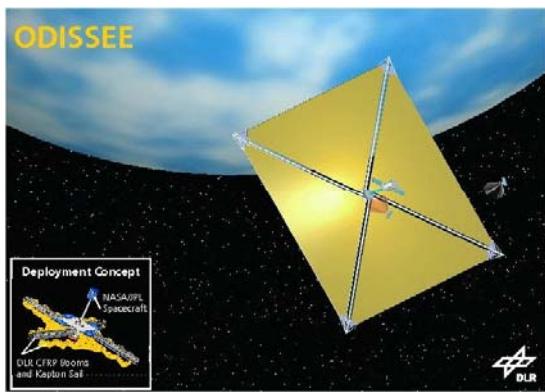
Advanced Manufacturing Technologies

Developed and refined the technology of sail assembly for manufacturing large monolithic sails, improving membrane coating processes and technologies



Sail sample with carbon black nanotubes

What About The Rest of the World?



- USA
 - The Planetary Society tried twice to fly a solar sail – both attempts suffered a launch vehicle failure
- Europe
 - The Odissee solar sail demonstration mission was not selected for flight
- Japan
 - Japan flew at least two tests of solar sail materials successfully – and had one failure

What Will Be Next?

- USA
 - NASA: No missions planned after NanoSail-D
 - The Planetary Society may try again to fly Cosmos
- Japan
 - The Japanese will fly a solar sail in 2008/2009 with the goal of launching a solar sail mission to Jupiter in 2010
- Europe
 - No missions planned

